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(54) **LED CURRENT CONTROL**

(75) Inventors: **Wai-Keung Cheng**, Union City, CA (US); **Son Tran**, San Jose, CA (US)

(73) Assignee: **ALPHA AND OMEGA SEMICONDUCTOR INCORPORATED**, Sunnyvale, CA (US)

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H05B 33/08 (2006.01)

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CPC ***H05B 33/0827*** (2013.01); ***H05B 33/0818*** (2013.01); ***H05B 37/02*** (2013.01); *Y02B 20/347* (2013.01)

(58) **Field of Classification Search**
CPC H05B 33/0821; H05B 33/0839; H05B 33/08; H05B 37/02
USPC .... 315/308, 312, 185 R, 191–193, 291, 315/307, 360
See application file for complete search history.

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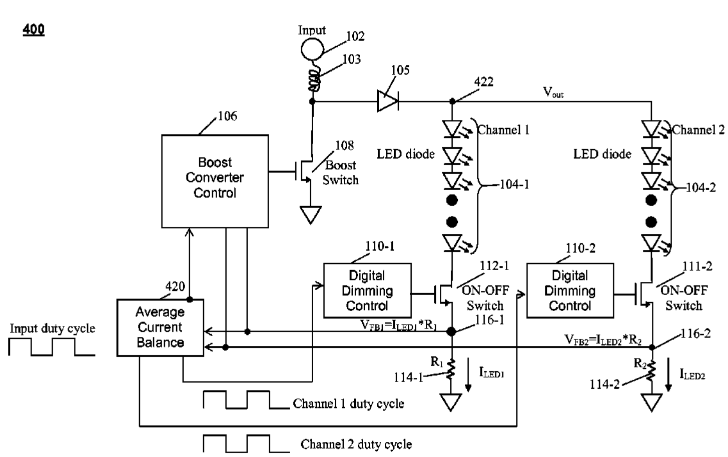
Primary Examiner — Tung X Le
(74) *Attorney, Agent, or Firm* — Joshua D. Isenberg; JDI Patent

(57) **ABSTRACT**

Parallel light emitting diode channels may be controlled using a pulsed control signal input characterized by an input duty cycle and one or more current sense input signals. Each of the one or more current sense input signals is indicative of a current through a corresponding load channel of one or more load channels. One or more pulsed channel current control signals are provided to one or more corresponding dimming controls correspondingly coupled to the one or more load channels. Each of the dimming controls is configured to provide an output signal to a corresponding ON-OFF switch, each of which is coupled in series with a corresponding the load channels. The channel duty cycle of each channel current control signal is adjusted relative to the input duty cycle in response to the current sense input signals.

23 Claims, 7 Drawing Sheets



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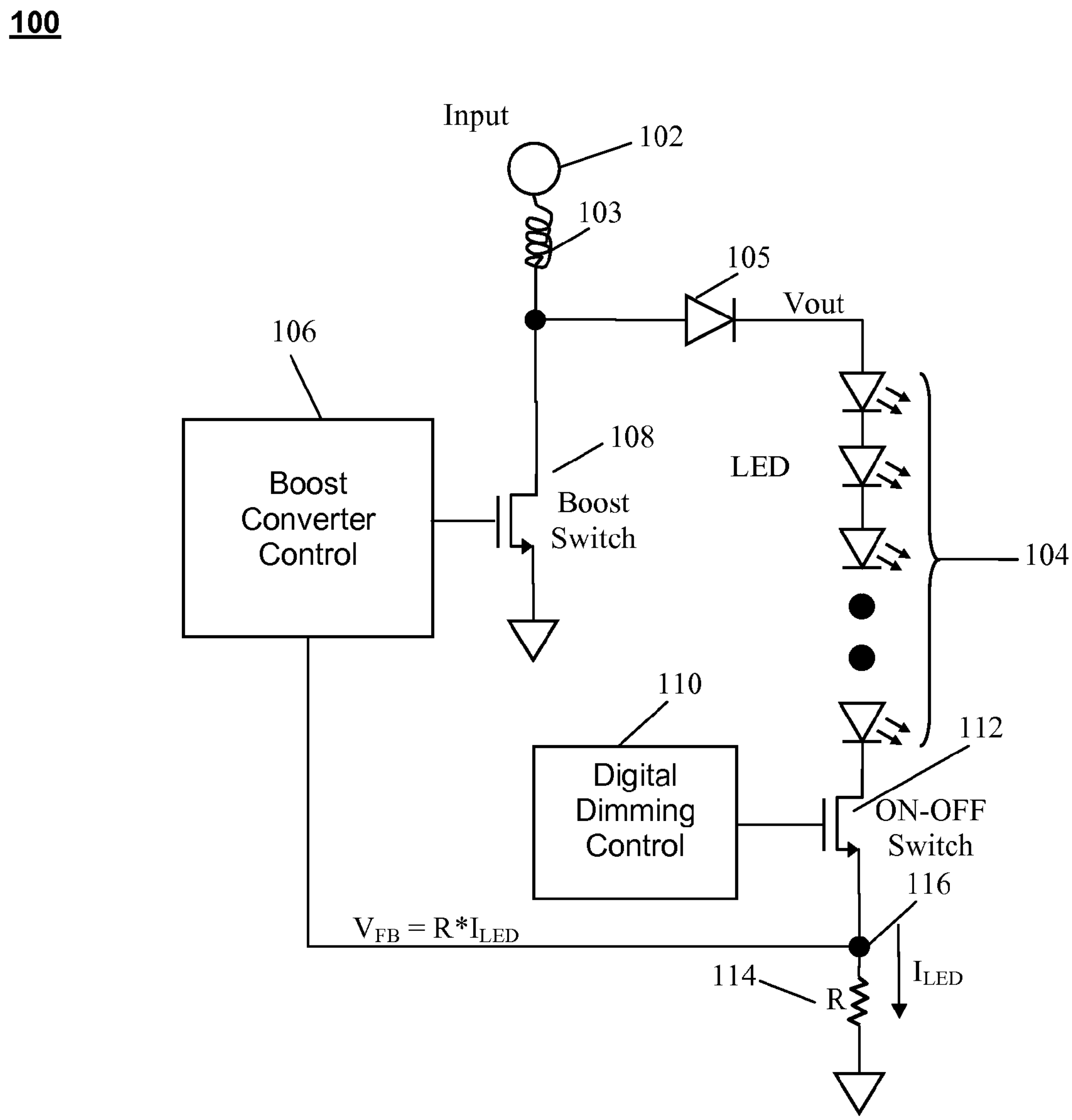

FIG. 1
(prior art)

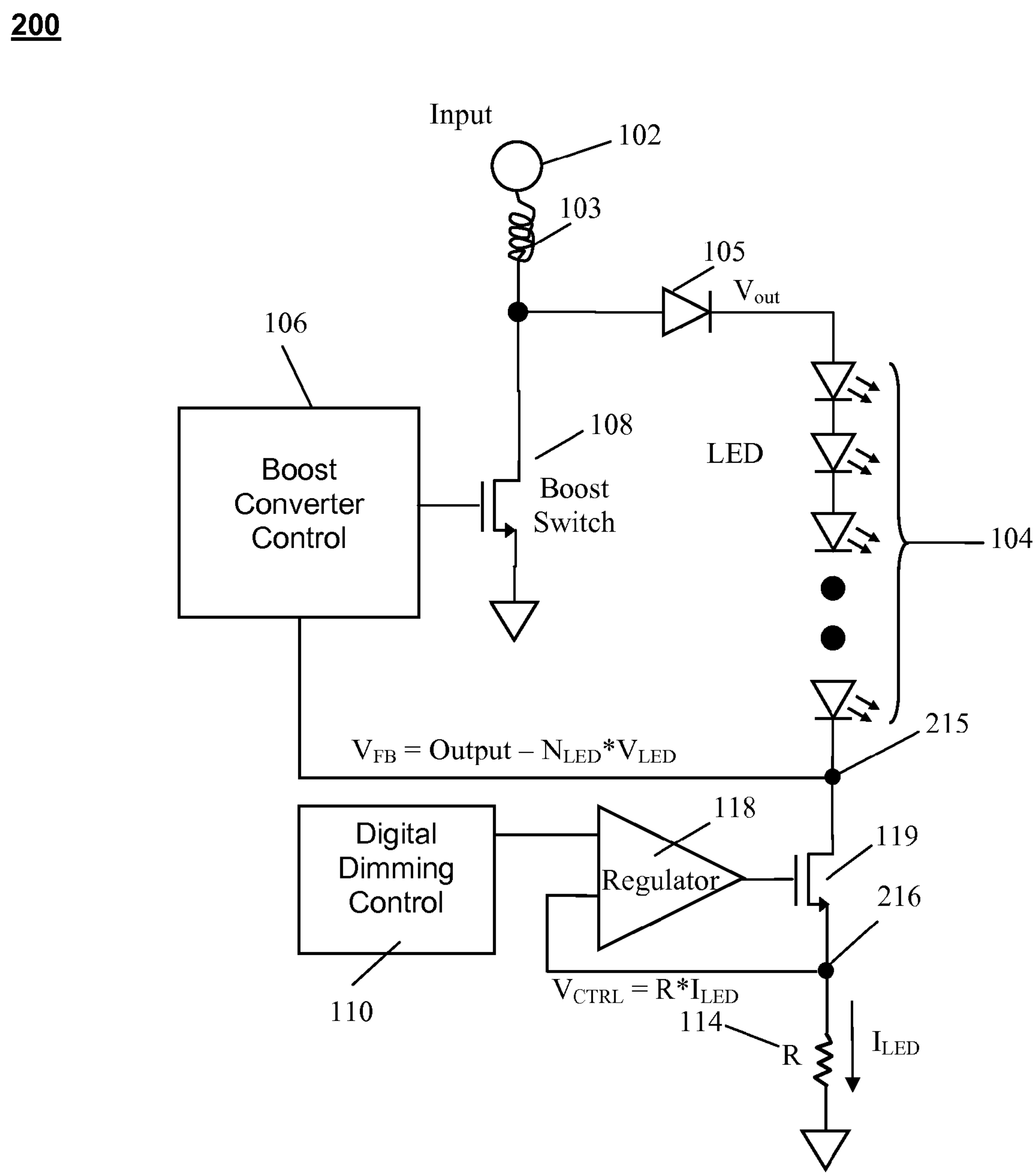

FIG. 2
(prior art)

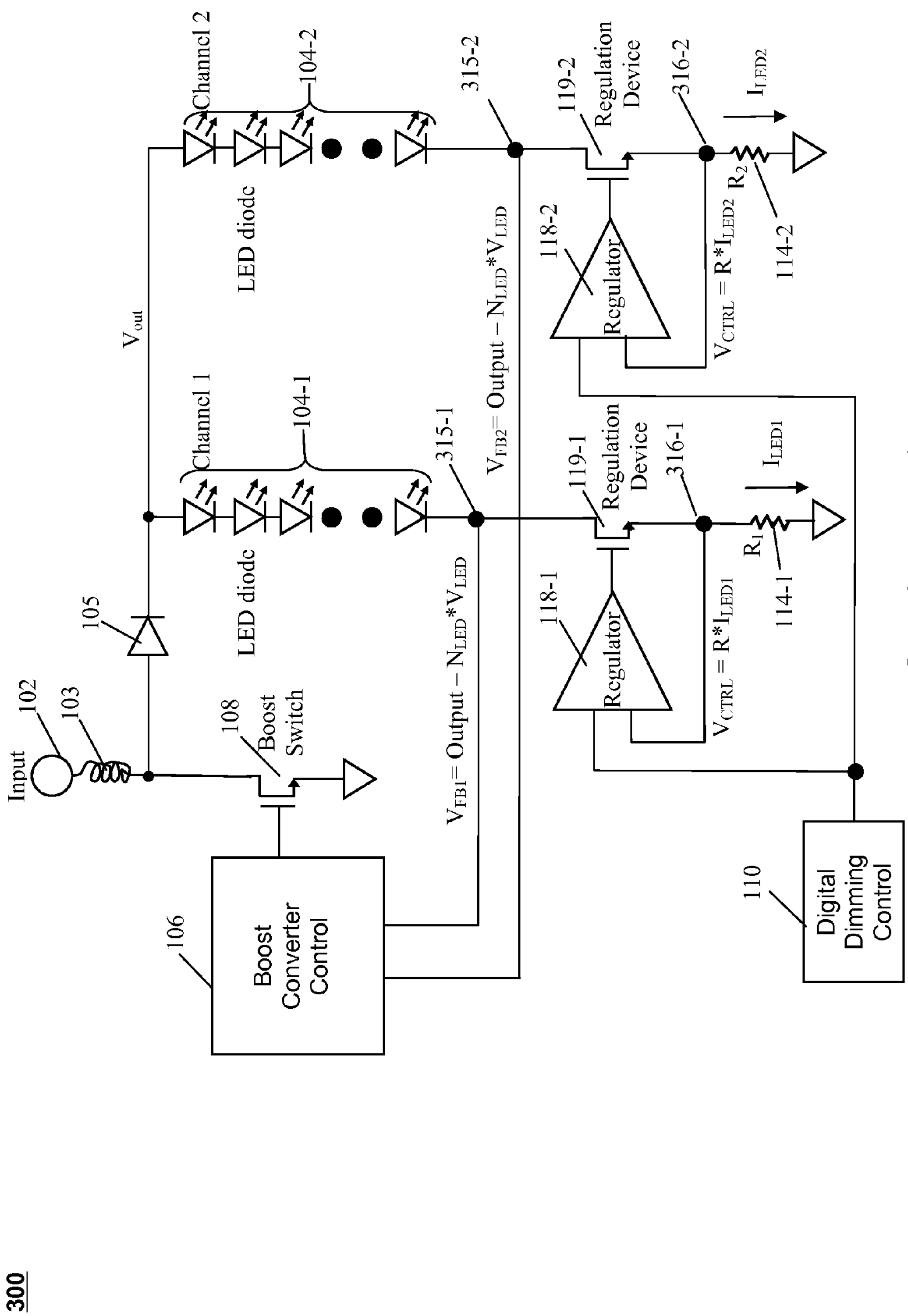

FIG. 3 (prior Art)

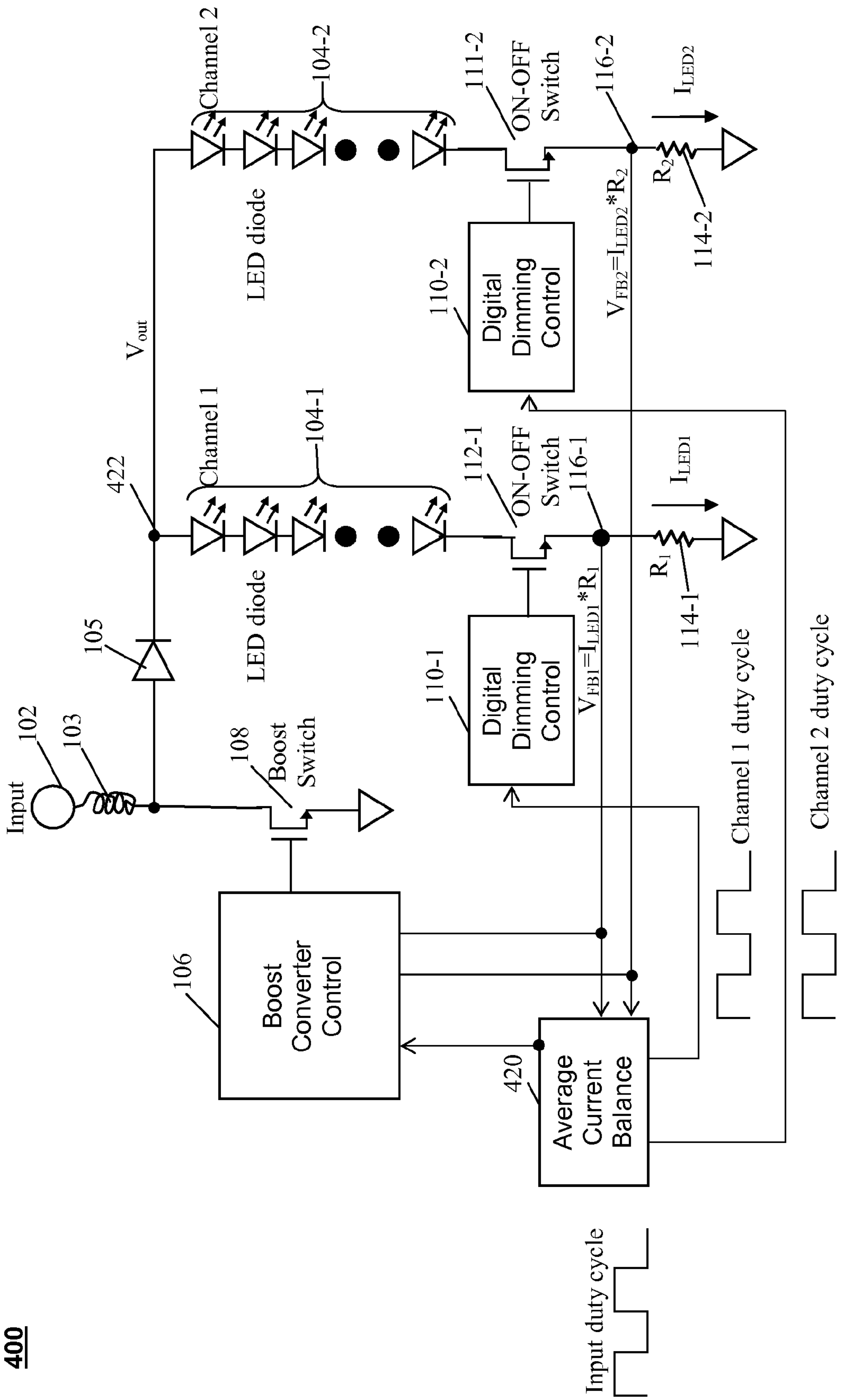
400
Input
102
103
105
106
Boost Converter Control
108
Boost Switch
422
V_{out}
Channel 1
104-1
LED diode
Channel 2
104-2
LED diode
110-1
Digital Dimming Control
110-2
Digital Dimming Control
112-1
ON-OFF Switch
111-2
ON-OFF Switch
116-1
116-2
$V_{FB1}=I_{LED1}*R_1$
$V_{FB2}=I_{LED2}*R_2$
R_1
R_2
114-1
114-2
I_{LED1}
I_{LED2}
420
Average Current Balance
Input duty cycle
Channel 1 duty cycle
Channel 2 duty cycle

FIG. 4

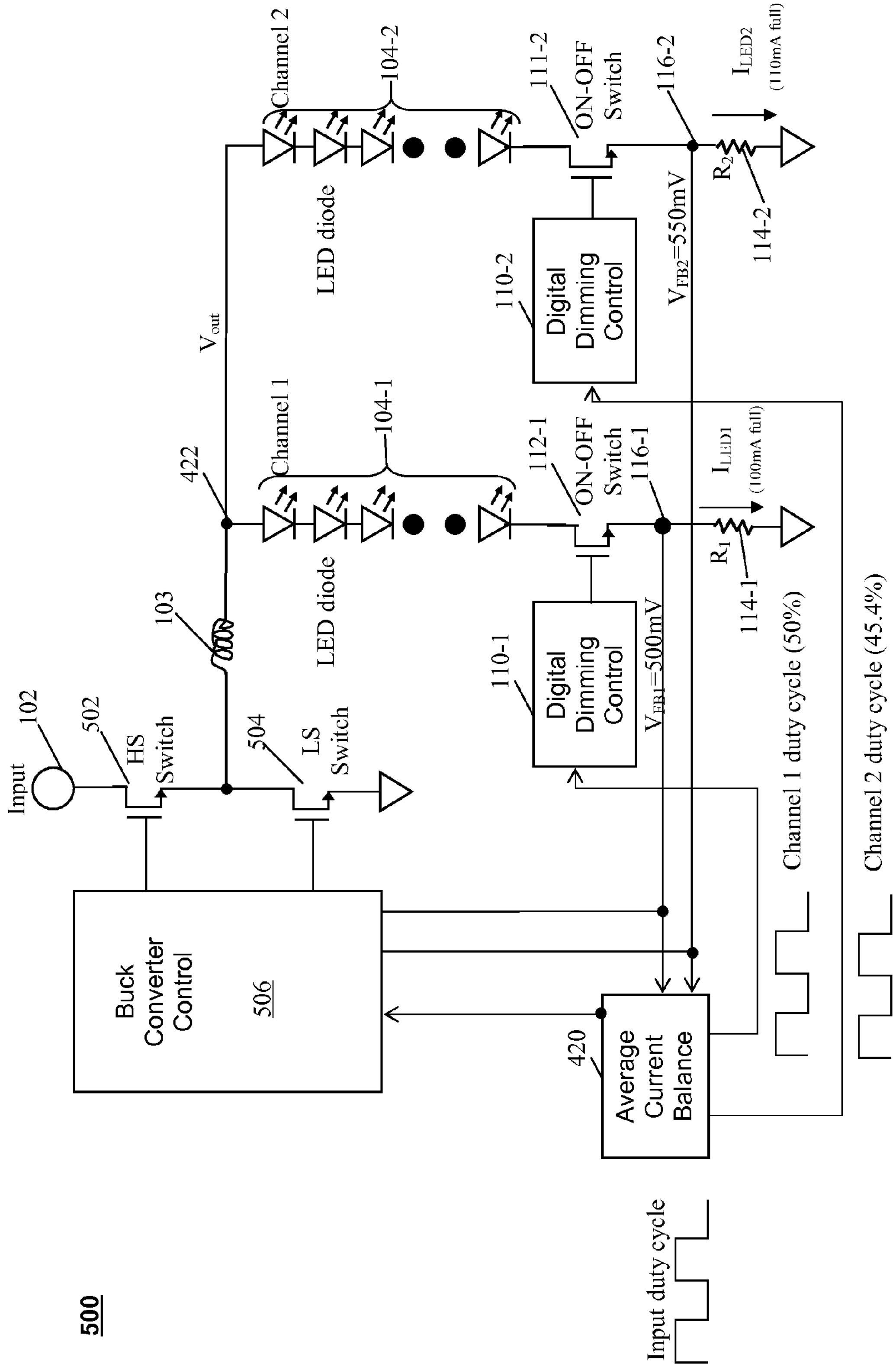
500
Input
102
502
HS Switch
504
LS Switch
103
422
V_{out}
Buck Converter Control
506
Channel 1
104-1
LED diode
Channel 2
104-2
LED diode
112-1
ON-OFF Switch
111-2
ON-OFF Switch
116-1
116-2
I_{LED1} (100mA full)
I_{LED2} (110mA full)
R_1
R_2
114-1
114-2
110-1
Digital Dimming Control
110-2
Digital Dimming Control
V_{FB1}=500mV
V_{FB2}=550mV
420
Average Current Balance
Input duty cycle
Channel 1 duty cycle (50%)
Channel 2 duty cycle (45.4%)

FIG. 5

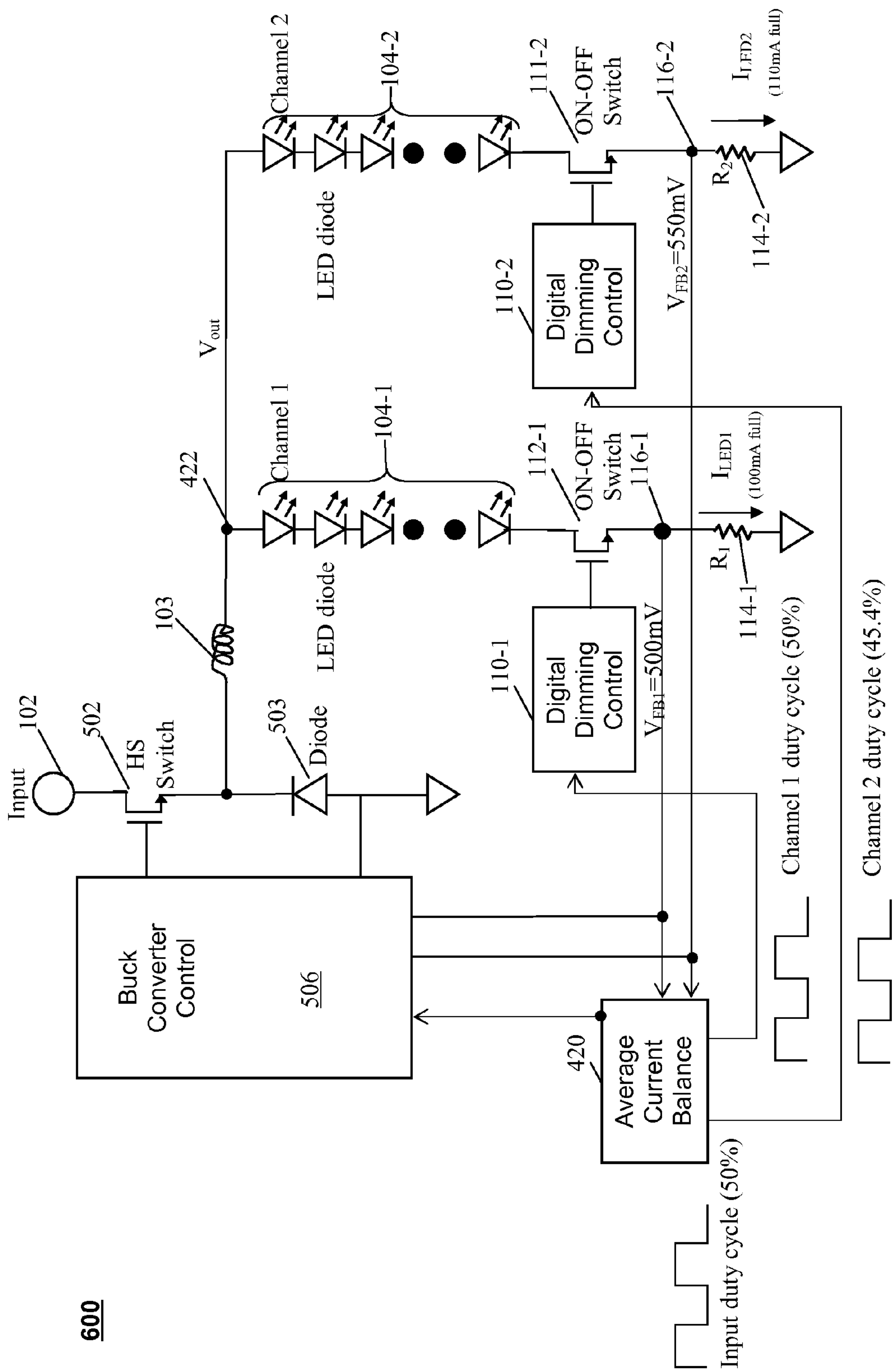
600
Input
102
502
HS Switch
503
Diode
103
422
Vout
Buck Converter Control
506
Average Current Balance
420
Input duty cycle (50%)
LED diode
Channel 1
104-1
112-1
ON-OFF Switch
116-1
Digital Dimming Control
110-1
V_{FB1}=500mV
I_{LED1}
(100mA full)
R_1
114-1
Channel 1 duty cycle (50%)
Channel 2
104-2
111-2
ON-OFF Switch
116-2
Digital Dimming Control
110-2
V_{FB2}=550mV
I_{LED2}
(110mA full)
R_2
114-2
Channel 2 duty cycle (45.4%)

FIG. 6

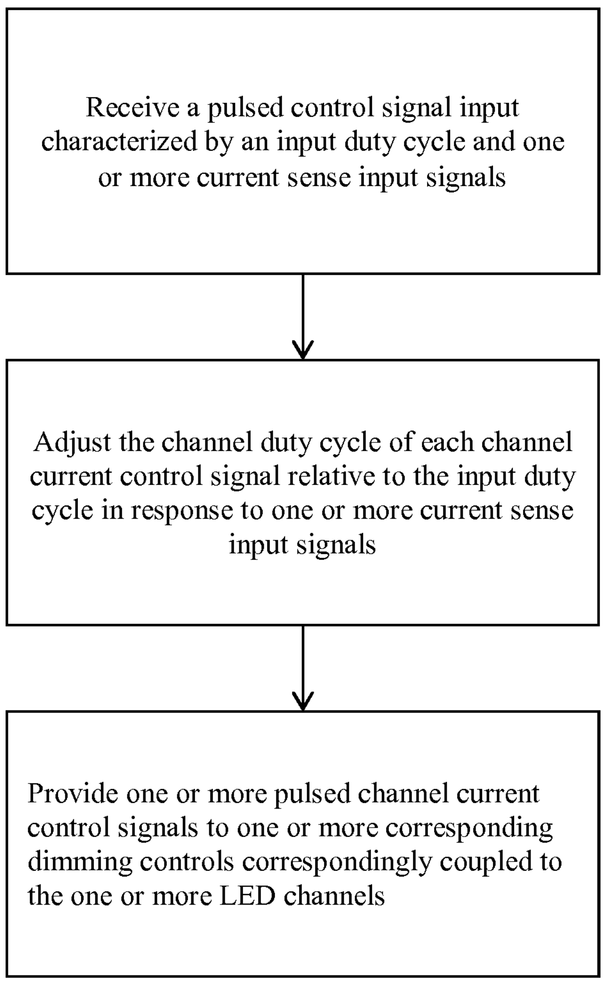
Receive a pulsed control signal input characterized by an input duty cycle and one or more current sense input signals
Adjust the channel duty cycle of each channel current control signal relative to the input duty cycle in response to one or more current sense input signals
Provide one or more pulsed channel current control signals to one or more corresponding dimming controls correspondingly coupled to the one or more LED channels

FIG. 7

LED CURRENT CONTROL

FIELD OF THE INVENTION

This invention relates in general to controlling multiple channels of light emitting diodes (LEDs) and in particular to the boost converter to drive multiple channels of LEDs using average current balance.

BACKGROUND OF THE INVENTIONS

Increasingly, many industrial, commercial, and public infrastructure applications have utilized light emitting diodes for lighting. Compared with previous lighting techniques such as incandescent or fluorescent lighting, LEDs can provide, a broad color spectrum, compact size, increased energy efficiency, absence of mercury and related environmental concerns, increased operating life, ability to dim output, absence of infrared or ultraviolet spectral components (when desired), and low voltage (on a per LED basis).

The emergence of high brightness light emitting diodes (HB-LEDs) may have improved aspects of solid state lighting solutions, which may provide performance advantages over conventional lighting technology. Higher optical efficiency, long operating lifetimes, wide operating temperature range and environmentally friendly implementation may be some of the key advantages of LED technology over incandescent or gas discharge light source solutions. However, manufacturing variations in forward voltage drop, luminous flux output, and/or peak wavelength may necessitate binning strategies, which may result in relatively lower yield and increased cost. Furthermore, a large number of LEDs, with matched characteristics, arranged in a suitable optical housing, may be required to meet the desired optical and luminance performance requirements. Dimming requirements and the need for circuit compensation techniques to regulate light output over a range of temperatures, and lifetime of the hardware may render a resistor biased drive solution obsolete for modern LED.

Various circuit techniques based on switching and linear regulating devices may have been described for driving a single "string" of series LEDs with precise forward current regulation and pulse modulation based dimming techniques. Such architectures may require a dedicated drive circuit for each LED string, and therefore may not be suitable for controlling a large number of strings.

It is within this context that embodiments of the present invention arise.

BRIEF DESCRIPTION OF THE DRAWINGS

Other objects and advantages of the invention will become apparent upon reading the following detailed description and upon reference to the accompanying drawings in which:

FIG. **1** is a schematic diagram of a conventional system capable of regulating a single channel (or string) of LEDs.

FIG. **2** is a schematic diagram of another conventional system capable of regulating a single channel of LEDs.

FIG. **3** is a schematic diagram of yet another conventional system, similar to the one in FIG. **2**, capable of regulating multiple channels/strings of LEDs.

FIG. **4** is a schematic diagram of a system capable of regulating a single LED channel or multiple channels of LEDs with a single boost converter according to an embodiment of the present invention.

FIG. **5** is a schematic diagram of a system capable of regulating a single LED channel or multiple channels of LEDs with a single buck converter according to another embodiment of the present invention.

FIG. **6** is a schematic diagram of a system capable of regulating a single LED channel or multiple channels of LEDs with a single buck converter according to alternative embodiment of the present invention.

FIG. **7** is a diagram showing the functions that an average current balance element is configured to perform according to one embodiment of the present disclosure.

DESCRIPTION OF THE SPECIFIC EMBODIMENTS

In the following Detailed Description, reference is made to the accompanying drawings, which form a part hereof, and in which is shown by way of illustration specific embodiments in which the invention may be practiced. In this regard, directional terminology, such as "top," "bottom," "front," "back," "leading," "trailing," etc., is used with reference to the orientation of the figure(s) being described. Because components of embodiments of the present invention can be positioned in a number of different orientations, the directional terminology is used for purposes of illustration and is in no way limiting. It is to be understood that other embodiments may be utilized and structural or logical changes may be made without departing from the scope of the present invention. The following detailed description, therefore, is not to be taken in a limiting sense, and the scope of the present invention is defined by the appended claims.

Introduction

Conventional LED backlight drivers typically include a boost or buck converter element that supplies the LED bias voltage and a current regulator element that controls the LED current. The driver may adjust the current in response to a control input, which may include a dimming or light level command. The driver may process the control input to provide coordinated responses by the boost or buck and current regulator elements. Inefficiencies may be reduced at least in part by performing phase shifted pulse width modulation (PS-PWM) of the LED strings, which may eliminate pulsed currents from the converter output, and may provide dynamic bus voltage regulation for improved efficiency.

There are generally two conventional methods that are used currently as described in FIGS. **1**, **2** and **3** as follows.

FIG. **1** is a schematic diagram showing a conventional LED driver system **100** capable of regulating a single channel (or string) of LEDs. Such a system may be used to control a bank of LEDs designed for an LED backlight. The system **100** may include a power source **102** coupled to a single channel of LEDs **104** through an inductor **103** and a Schottky diode **105**. The power source **102** is through the inductor **103** and a boost switch **108** to ground (or some other voltage reference). The boost switch **108** is a "throttle" type switch in which the instantaneous current through the switch depends on the level of an output signal from a Boost Converter Control **106**. Current flows through the inductor **103** when the boost switch **108** is turned on, thereby building up voltage. When the boost switch is off energy stored in the inductor **103** is dumped through a Schottky diode to the LED channel **104**.

The system **100** may also include a digital dimming control **110** coupled to LED channel **104** through an ON-OFF switch **112** and a current sense resistor **114** located between the ON-OFF switch **112** and ground, which also is coupled to the boost converter control **106**. Because the sense resistor is in series with the LED channel **104**, the voltage across the sense resistor **114** is proportional to the current through the sense resistor **114**, which is the current (I_{LED}) through the LED channel **104**. In the system **100**, the boost voltage across the LED channel **104** is regulated by controlling the current through the boost switch **108** in response to a voltage measured across the sense resistor **114**. The average LED current (I_{LED}) is regulated in response to a signal from the dimming control **110**. The ON-OFF switch **112** between the sense resistor **114** and the cathode of lowest LED turns the current through the LED channel **104** on and off in response to signals from the dimming control **110**. The dimming control **110** adjusts the average current by changing the duty cycle with which the ON-OFF switch **112** turns the current on and off.

The system **100** may implement one control loop to regulate the LED bias voltage V_{LED} at the node **116**. A feedback circuit is formed by coupling the LED bias voltage V_{LED} (node **116**) back to the boost converter control **106** as a feedback voltage V_{FB} (V_{FB}=R*I_{LED}) to implement boost voltage regulation. Due to mismatch of the forward voltages between different LED's, this method is typically used for a single LED channel. This technique is based on use of an individual boost converter control, so for a multi-channel LED system, for example two LED channels, the technique would require two inductors, two boost switches and two ON-OFF switches. Such a system can be undesirably expensive due to the multiple boost switches for boost converter and multiple buck switches for buck converter for each channel.

FIG. **2** is a schematic diagram showing a conventional boost converter **200** capable of regulating a single channel (or string) of LEDs. Similar to system **100**, system **200** may include a power source **102** coupled to a single channel of LEDs **104** through an inductor **103** and a Schottky diode **105**. The power source **102** also is coupled through a boost switch **108** to ground or some other voltage reference. In system **200**, the boost voltage is regulated in response to a feedback voltage V_{FB}, which is measured at the cathode of the lowest LED diode in the channel **104** at node **215**.

In this method, the system **200** implements a first control loop to regulate the Output voltage across the LED channel **104** in response to the feedback voltage at the node **215**. If the voltage drop across each LED is assumed to be the same, the feedback voltage V_{FB} may be expressed as Output−N_{LED}*V_{LED}, where N_{LED} is the number of LEDs in channel **104**. A feedback circuit is formed by coupling the feedback voltage V_{FB} at node **215** to a boost converter control **106** that provides a boost control signal to the boost switch **108** to implement boost voltage regulation.

Since the first feedback loop does not regulate the current I_{LED} through the LED channel **104**, a current regulation device **218** is coupled between the LED channel **104** and ground. A sense resistor **114** is coupled between the current regulation device **119** (e.g., a linear switch or transistor) and ground. A signal from a regulator **118** is applied to the regulation device to control the LED current. The regulator **118** may be a comparator that receives a control input, e.g., a voltage that corresponds to the channel current I_{LED}. The control input may be in the form of a voltage V_{CTRL} measured at a node **216** between the regulation device **119** and a sense resistor R coupled to ground, where V_{CTRL}=R*I_{LED}. The regulator **118** may compare the control input to a second control input that corresponds to a desired value for the channel current I_{LED}.

In the system **200**, because current is regulated independently of voltage, this system also can be used for multi-channel configuration, i.e., it is used to match the current of each LED channel. FIG. **3** is a schematic diagram of another conventional system **300**, similar to the one in FIG. **2**, capable of regulating multiple channels/strings of LEDs. Unfortunately, there are similar cost issues with the system **200** of FIG. **2** as with the system **100** of FIG. **1** that make such a system undesirably expensive for multi-channel implementations. The cost of such a system is partly driven by the cost of implementing the LED current regulator in silicon using a traditional IC process and engineering design resources. In addition, the LED current regulator device **119** typically operates in a linear region, which is not as efficient as an on-off switch in terms of power consumption and device size. Although a multi-channel version of the system **200** does not need multiple boost converters or multiple boost switches to regulate multiple parallel channels, such a system would require multiple regulators and multiple current regulation devices.

FIG. **3** depicts a multi-channel LED control system **300**. Similar to system **200**, system **300** may include a power source **102** coupled to multiple parallel channels of LEDs **104**, for a simplicity, only two channels **104-1** and **104-2** are shown in FIG. **3**. A power source **102** is coupled to a multiple parallel channels of LEDs through an inductor **103** and a Schottky diode **105** to provide an output voltage V_{OUT}. The power source **102** also is coupled through a boost switch **108** to ground or some other voltage reference. A boost converter control **106** provides a signal that controls the boost switch **108**.

The system **300** implements a first control loop to regulate the LED bias voltage V_{LED} at the node **315-1**. A feedback circuit is formed by coupling a feedback voltage V_{FB} from node **315-1** back to the boost converter control **106**. Again, assuming each LED in channel **104-1** has the same voltage drop, V_{FB1}=V_{OUT}−V_{LED}*N_{LED}, where N_{LED} is the number of LED in the first channel **104-1**. The system **300** also implements a second control loop to regulate the LED bias voltage V_{LED} at the node **315-2**. A feedback circuit is formed by coupling the feedback voltage V_{FB2} at node **315-2** back to the boost converter control **106** as a feedback voltage V_{FB2} (V_{FB2}=V_{OUT}−V_{LED}*N_{LED}), where N_{LED} is the number of LED in the second LED channel **104-2**. The boost voltage is regulated by the lowest feedback voltage, VF_{B1} or VF_{B2}, which corresponds to the LED channel having the highest voltage drop across it.

Similar to system **200**, system **300** further includes current regulators **118-1** and **118-2** to control the LED current, which are used between the cathode of the lowest LED diodes in the channels **104-1** and **104-2** respectively to ground. In system **300**, the digital dimming control **110** is coupled to the regulators **118-1** and **118-2**. Third and fourth control loops are implemented to independently regulate the LED currents (I_{LED1} and I_{LED2}) at the node **316-1** and node **316-2** respectively. Typically, a feedback circuit is formed by coupling the LED current I_{LED1} (node **316-1**) back to the regulator **118-1** as a control voltage V_{CTRL} (V_{CTRL}=R*I_{LED1}) to implement current regulation through a regulation device **119-1** and a feedback circuit is formed by coupling the LED current I_{LED2} (node **316-2**) back to the regulator **118-2** as a control voltage V_{CTRL} (V_{CTRL}=R*I_{LED2}) to implement current regulation through a regulation device **119-2**. This method is a more costly solution due to the use of multiple regulators and regulation devices. The system **300** in the example depicted in FIG. **3** requires one inductor, one boost switch, two regulators and two regulation devices for 2 channels system. Beside, power is wasted for the channels other than the one with the lowest

LED forward voltage. Specifically, since the voltage is regulated based on the channel having the lowest feedback voltage the channels with higher feedback voltages will have power lost to dissipation as heat in their regulation devices.

Solution

System **100** of FIG. **1** is the most cost efficient solution for LED backlight. However, the cost efficiency diminishes for more than one channel due to duplicate boost or buck converter elements. Embodiments of the present invention system adapt an LED control system like the system **100** for control of multiple channels with single boost converter element.

Specifically, the drawbacks associated with prior art LED controls may be avoided by controlling parallel light emitting diode channels may be controlled using a pulsed control signal input characterized by an input duty cycle and one or more current sense input signals. Each current sense input signal is indicative of a current through a corresponding LED channel. One or more pulsed channel current control signals can be provided to one or more corresponding dimming controls correspondingly coupled to the one or more LED channels. Each of the dimming controls is configured to provide an output signal to a corresponding ON-OFF switch, each of which is coupled in series with a corresponding the LED channels. The channel duty cycle of each channel current control signal is adjusted relative to the input duty cycle in response to the current sense input signals.

By using ON-OFF switches and dimming controls instead of linear switches and regulators the cost of the control system can be significantly reduced.

Embodiment

FIG. **4** is a schematic diagram of a system **400** capable of regulating multiple channels of LEDs with a single boost converter, resulting in cost efficiency, according to an embodiment of the present invention.

In the system **400** multiple parallel channels of LEDs may be coupled to the power source **102** via a Schottky diode **105** and inductor **103**. The voltage across each channel is the output voltage V_{out} at the cathode of the Schottky diode **105**. In the example, depicted in FIG. **4**, two LED channels **104-1**, **104-2** are shown; however, embodiments of the invention may be implemented with any number of LED channels. The voltage drop across each individual LED channel may vary with the individual characteristics of the LEDs, such that the different LED channels may have different activation voltages. For simplicity, system **400** only shows two channels of LEDs **104-1** and **104-2**. The power source **102** also is coupled to a Boost Converter Control **106** through a boost switch **108**. Similar to system **100**, each digital dimming control **110-1**, **110-2** is coupled to a corresponding LED channel **104-1**, **104-2** through an ON-OFF switch **112-1**, **112-2** and a current sense resistor **114-1**, **114-2** located between the ON-OFF switch **112-1**, **112-2** and ground or some other voltage reference.

As shown in FIG. **4**, each digital dimming control **110-1**, **110-2** provides a control signal to it corresponding ON-OFF switch **112-1**, **112-2** to control the current I_{LED1}, I_{LED2} through the corresponding LED channel **104-1**, **104-2** by pulse width modulation.

The system **400** implements separate feedback loops to regulate the output voltage V_{OUT} and the average current of the channels **104-1**, **104-2** in response to sense signals corresponding to the instantaneous currents I_{LED1}, I_{LED2} through LED channels **104-1**, **104-2**. By way of example, and not by way of limitation, the sense signals may be in the form of feedback signals V_{FB1}, V_{FB2} measured at nodes **116-1** and **116-2** between sense resistors **114-1**, **114-2** and ON-OFF switches **112-1**, **112-2**. The feedback voltages V_{FB1}, V_{FB2} may be expressed as $V_{FB1}=R_1*I_{LED1}$ and $V_{FB2}=R_2*I_{LED2}$. Similar to system **300**, output voltage control feedback loops for the LED channels **104-1**, **104-2** may be formed by coupling the feedback voltages V_{FB1}, V_{FB2} to the boost converter control **106**. The boost converter control **106** may choose the lowest feedback voltage of V_{FB1}, V_{FB2} to regulate the output voltage V_{OUT} as this is the minimum output voltage required to keep channel on.

The system **400** further includes an Average Current Balance Element **420** coupled to the digital dimming controls **110-1**, **110-2** and to the Boost converter control **106**. In this method, the average current for each channel **104-1**, **104-2** is regulated instead of the instantaneous current, as in the system **300**. The average current balance element **420** is configured to receive a pulsed control signal input characterized by an input duty cycle and current sense input signals corresponding to the current through each LED channel **104-1**, **104-2**. By way of example, and not by way of limitation, the current sense signals may be the feedback voltages V_{FB1}, V_{FB2} or signals derived from them. The average current balance element is further configured to provide pulsed channel current control signals to the digital dimming controls **110-1**, **110-2**. The average current balance element **420** is configured to adjust the channel duty cycle of each channel current control signal relative to the input duty cycle in response to the one or more current sense input signals (e.g., in response to V_{FB1} and V_{FB2}).

By way of example, and not by way of limitation, the Average current balance element **420** may be implemented in software in a programmable device, such as a microprocessor or in hardware, such as an application specific integrated circuit ASIC, or a microcontroller. FIG. **7** is a diagram showing the functions that an average current balance element **420** is configured to perform.

To control the average current through each LED channel **104-1**, **104-2**, the average current balance element **420** provides separate pulse width modulation inputs to the digital dimming controls **110-1**, **110-2** to achieve the same average current I_{LED1} for each LED channel with the same output voltage V_{OUT} at the anode of the top LED diode (node **422**) for all channels. Average Current Balance element **420** uses the current information to determine the channel with the lowest LED current. This channel will provide feedback signal for boost converter regulation. The ON-OFF switch duty cycle for the channel with the lowest LED current will be the same as the input PWM dimming duty cycle. All other channels with higher LED current will have the ON-OFF switch duty cycle adjusted by the difference of LED current. The channel duty cycle for LED channels having higher LED channel currents I_{LED} (higher) than the lowest LED channel current I_{LED}(lowest) may be expressed by the following equation:

$$\text{Channel duty cycle}=[I_{LED}(\text{lowest})*\text{Input Duty Cycle}]/I_{LED}(\text{higher})].$$

By way of numerical example, assume the two channels **104-1**, **104-2** are 10% mismatched. With the same output voltage V_{OUT} at anode of the top LED diode (node **422**), if the full current I_{LED1} of channel **104-1** is 100 mA, due to the 10% mismatch, the full current of channel **104-2** would be 110 mA. Therefore, the feedback voltage V_{FB1} of channel **104-1** would be 500 mV and the feedback voltage V_{FB2} of channel **104-2** would be 550 mV due to LED 10% mismatch. For the sake of example it is assumed that $R_1=R_2$.

The boost converter control **106** will choose the lowest feedback voltage, in this example V_{FB1} of 500 mV to regulate the output voltage V_{OUT} as this is the minimum output voltage required to keep LED channel **104-1** on.

Assume the input duty cycle is 50%. If the same duty cycle were applied to the digital dimming controls, the resulting average currents would be 50 mA for the first channel **104-1** and 55 mA for the second channel **104-2**. The Average Current Balance **420** adjusts the duty cycle for the second LED channel **104-2** from 50% to 45.4% so that the average current I_{LED2} for the second channel is 50 mA (110 mA*0.454=50 mA).

Embodiments of the present invention are not limited to implementations that utilize a boost converter. In alternative embodiments, a single buck converter may be used in an LED drive to step down an input voltage. By way of example, and not by way of limitation, FIG. **5** is a schematic diagram of a system **500** capable of regulating multiple channels of LEDs with a single buck converter, resulting in cost efficiency, according to an embodiment of the present invention.

The system **500** is basically similar to system **400** except that a boost converter control is replaced with a buck converter control. The illustrated system **500** is a synchronous buck configuration, which includes a high-side (HS) switch **502** and a low-side (LS) switch **504** electrically coupled to the Buck Converter Control **506**. The HS and LS switches can be suitable transistors, e.g., MOSFET, IGBT or BJT.

In the system **500** multiple parallel channels of LEDs may be coupled to the power source **102** via an inductor **103** and the HS switch **502** or the LS switch **504**. The voltage across each channel is the output voltage V_{out} cross the inductor **103**. In the example, depicted in FIG. **5**, two LED channels **104-1**, **104-2** are shown; however, embodiments of the invention may be implemented with any number of LED channels. The voltage drop across each individual LED channel may vary with the individual characteristics of the LEDs, such that the different LED channels may have different activation voltages. For simplicity, system **500** only shows two channels of LEDs **104-1** and **104-2**. The power source **102** also is coupled to the Buck Converter Control **506** through the HS switch **502** and LS switch **504**. Similar to system **400**, each digital dimming control **110-1**, **110-2** is coupled to a corresponding LED channel **104-1**, **104-2** through an ON-OFF switch **112-1**, **112-2** and a current sense resistor **114-1**, **114-2** located between the ON-OFF switch **112-1**, **112-2** and ground or some other voltage reference. Each digital dimming control **110-1**, **110-2** provides a control signal to it corresponding ON-OFF switch **112-1**, **112-2** to control the current I_{LED1}, I_{LED2} through the corresponding LED channel **104-1**, **104-2** by pulse width modulation.

Similar to system **400**, the system **500** implements separate feedback loops to regulate the output voltage V_{OUT} and the average current of the channels **104-1**, **104-2** in response to sense signals corresponding to the instantaneous currents I_{LED1}, I_{LED2} through LED channels **104-1**, **104-2** as described above. The buck converter control **506** may choose the lowest feedback voltage of V_{FB1}, V_{FB2} to regulate the output voltage V_{OUT} as this is the minimum output voltage required to keep channel on. The system **500** further includes an Average Current Balance Element **420** coupled to the digital dimming controls **110-1**, **110-2** and to the Buck converter control **506**. The average current for each channel **104-1**, **104-2** is regulated instead of the instantaneous current, as in the system **300**. The average current balance element **420** is configured to receive a pulsed control signal input characterized by an input duty cycle and current sense input signals corresponding to the current through each LED channel **104-1**, **104-2**. By way of example, and not by way of limitation, the current sense signals may be the feedback voltages V_{FB1}, V_{FB2} or signals derived from them. The average current balance element is further configured to provide pulsed channel current control signals to the digital dimming controls **110-1**, **110-2**. The average current balance element **420** is configured to adjust the channel duty cycle of each channel current control signal relative to the input duty cycle in response to the one or more current sense input signals (e.g., in response to V_{FB1} and V_{FB2}).

When the HS switch is closed (ON state), thus the LS switch is opened (OFF state), the voltage across the inductor **103** is $V_L=V_{in}-V_{out}$. The current through the inductor **103** rises linearly. As the LS switch is OFF, no current flows through it. As describe above, to control the average current through each LED channel **104-1**, **104-2**, the average current element balance **420** provides separate pulse width modulation inputs to the digital dimming controls **110-1**, **110-2** to achieve the same average current I_{LED1} for each LED channel with the same output voltage V_{OUT} at the anode of the top LED diode (node **422**) for all channels. Average Current Balance **420** uses the current information to determine the channel with the lowest LED current. This channel will provide feedback signal for buck converter regulation. The ON-OFF switch duty cycle for the channel with the lowest LED current will be the same as the input PWM dimming duty cycle. All other channels with higher LED current will have the ON-OFF switch duty cycle adjusted by the difference of LED current. The channel duty cycle for LED channels having higher LED channel currents I_{LED} (higher) than the lowest LED channel current I_{LED}(lowest) may be expressed by the following equation:

$$\text{Channel duty cycle}=[I_{LED}(\text{lowest})*\text{Input Duty Cycle}]/I_{LED}(\text{higher})].$$

By way of numerical example, assume the two channels **104-1**, **104-2** are 10% mismatched. With the same output voltage V_{OUT} at anode of the top LED diode (node **422**), if the full current I_{LED1} of channel **104-1** is 100 mA, due to the 10% mismatch, the full current of channel **104-2** would be 110 mA. Therefore, the feedback voltage V_{FB1} of channel **104-1** would be 500 mV and the feedback voltage V_{FB2} of channel **104-2** would be 550 mV due to LED 10% mismatch. For the sake of example it is assumed that $R_1=R_2$.

The buck converter control **506** will choose the lowest feedback voltage, in this example V_{FB1} of 500 mV to regulate the output voltage V_{OUT} as this is the minimum output voltage required to keep LED channel **104-1** on.

Assume the input duty cycle is 50%. If the same duty cycle were applied to the digital dimming controls, the resulting average currents would be 50 mA for the first channel **104-1** and 55 mA for the second channel **104-2**. The Average Current Balance **420** adjusts the duty cycle for the second LED channel **104-2** from 50% to 45.4% so that the average current I_{LED2} for the second channel is 50 mA (110 mA*0.454=50 mA).

When the HS switch is opened (OFF state), thus the LS switch is closed (ON state), the voltage across the inductor **103** is $V_L=-V_{out}$ (neglecting diode drop). Thus, Current I_L though the inductor **103** decreases.

FIG. **6** is a schematic diagram of a system **600** capable of regulating multiple channels of LEDs with single buck converter, resulting in cost efficiency, according to another embodiment of the present invention. System **600** is similar to system **500** except that the system **600** is a non-synchronous buck configuration, which includes a high-side (HS) switch **502** and a diode **503** electrically coupled to the Buck Converter Control **506** and a diode **503**. The HS switch can be a suitable transistor, such as a MOSFET, IGBT or BJT. The diode is configured to be reverse biased when the HS switch **502** is closed and forward biased when the HS switch **502** is open. As is common in non-synchronous buck converters, the voltage across the parallel LED channels **104-1**, **104-2** depends on the duty cycle of the switch signal that turns the HS switch **502** on and off.

In the system **600** multiple parallel channels of LEDs may be coupled to the power source **102** via an inductor **103** and the HS switch **502** or the diode **503**. The voltage across each channel is the output voltage V_{out} across the inductor **103**. The power source **102** also is coupled to the Buck Converter Control **506** through the HS switch **502** and the diode **503**.

System **600** basically operates similar to system **500**. When the HS switch **502** is closed (ON state) the voltage across the inductor **103** is $V_L=V_{in}-V_{out}$. The current through the inductor **103** rises linearly. As the diode **503** is reverse-biased by the voltage source V, no current flows through it. When the HS switch **502** is opened (OFF state), the diode **503** is forward biased, the voltage across the inductor **103** is $V_L=-V_{out}$ (neglecting diode drop). Thus, Current I_L though the inductor **103** decreases. This technique for current control avoids power loss in channels having higher currents and reduces cost for the system by avoiding using expensive regulators and regulation devices, as in the system **300** of FIG. **3**. Although examples are described in terms of LED channels for backlights, those skilled in the art will recognize that embodiments of the present invention are not limited to such implementations. Alternatively, embodiments of the present invention may be employed in other applications where it is desirable to control the current in multiple parallel channels. In principle, embodiments of the present invention may be applied to any type of device that uses pulse width modulation to regulate average DC current in one or more load channels. Such, devices may include, e.g., motor drives.

While the above is a complete description of the preferred embodiments of the present invention, it is possible to use various alternatives, modifications, and equivalents. Therefore, the scope of the present invention should be determined not with reference to the above description but should, instead, be determined with reference to the appended claims, along with their full scope of equivalents. Any feature, whether preferred or not, may be combined with any other feature, whether preferred or not. In the claims that follow, the indefinite article "A" or "An" refers to a quantity of one or more of the item following the article, except where expressly stated otherwise. The appended claims are not to be interpreted as including means-plus-function limitations, unless such a limitation is explicitly recited in a given claim using the phrase "means for". Any element in a claim that does not explicitly state "means for" performing a specified function, is not to be interpreted as a "means" or "step" clause as specified in 35 USC §112, ¶6.

What is claimed is:

1. A light emitting diode (LED) control system, comprising:

two or more digital dimming controls, each of which is configured to receive a corresponding one of two or more pulsed channel current control signals, wherein each of the two or more pulsed channel current control signals is characterized by a corresponding channel duty cycle, wherein each of the two or more dimming controls is configured to provide an output signal directly coupled to a corresponding one of two or more ON-OFF switches without passing the output signal through a regulator, wherein each of said two or more ON-OFF switches is coupled in series with a corresponding one of a plurality of parallel LED channels; and

an average current balance element having circuitry configured to receive a pulsed control signal input characterized by an input duty cycle and two or more current sense input signals, wherein each of the two or more current sense input signals is indicative of a current through a corresponding one of the plurality of parallel LED channels, wherein the circuitry is further configured to provide the two or more pulsed channel current control signals to corresponding ones of the two or more digital dimming controls, wherein the circuitry is additionally configured to adjust the channel duty cycle of each of the two or more pulsed channel current control signals relative to the input duty cycle in response to the two or more current sense input signals.

2. The system of claim **1** wherein a particular channel with a lowest LED current has a channel duty cycle equal to the input duty cycle.

3. The system of claim **2** wherein each of the plurality of LED channels having a higher LED current than the lowest LED current has a channel duty cycle lower than the input duty cycle.

4. The system of claim **3**, wherein the channel duty cycle for a given LED channel other than the particular LED channel having the lowest LED current is equal to a product of the input duty cycle and a ratio of the lowest LED channel current to a channel current for the given channel.

5. The system of claim **2**, wherein each of the two or more ON-OFF switches is coupled between a corresponding sense resistor and one end of a corresponding LED channel that is coupled to the corresponding sense resistor.

6. The system of claim **1**, further comprising a single boost converter element configured to sense a channel current through each of the plurality of parallel LED channels and regulate a drive voltage supplied to the parallel LED channels.

7. The system of claim **6**, wherein the boost converter is configured to receive the two or more current sense input signals, determine a boost switch signal from the two or more current sense input signals, and provide the boost switch signal to a boost switch that is configured to regulate the drive voltage by regulating a current through the boost switch.

8. The system of claim **7**, further comprising a boost switch, wherein the boost switch is coupled between a node and a voltage reference, where the node is coupled to an input side of the plurality of parallel LED channels.

9. The system of claim **8**, further comprising an inductor, wherein the inductor is coupled between the node and a source of input voltage.

10. The system of claim **1**, further comprising a single buck converter element configured to sense a channel current through each of the plurality of parallel LED channels and provide two or more switch signals to two or more switches that regulate a drive voltage supplied to the plurality of parallel LED channels.

11. The system of claim **10**, wherein the buck converter is a synchronous buck converter configured to receive the two or more current sense input signals, determine a high-side switch signal and a low side switch signal from the two or more current sense input signals, and provide the high-side switch signal to a high-side switch coupled between a voltage source and a node and the low-side signal to a low-side switch coupled between the node and a reference voltage.

12. The system of claim **11**, further comprising the high side switch and the low side switch.

13. The system of claim **12**, further comprising an inductor, wherein the inductor is coupled between the node and the plurality of parallel LED channels.

14. The system of claim **10**, wherein the buck converter is a non-synchronous buck converter configured to receive the two or more current sense input signals, determine a high-side switch signal and provide the high-side switch signal to a high-side switch coupled between a voltage source and a node that is connected to the plurality of LED channels through an inductor.

15. The system of claim **14**, further comprising a diode coupled between the node and a reference voltage, wherein the diode is configured to be reverse biased when the high-side switch is open.

16. A current control system, comprising:

an average current balance element having circuitry configured to receive a pulsed control signal input characterized by an input duty cycle and two or more current sense input signals, wherein each of the two or more current sense input signals is indicative of a current through a corresponding load channel of a plurality of load channels, wherein the average current balance element is configured to provide two or more pulsed channel current control signals to two or more corresponding dimming controls correspondingly directly coupled to the plurality of load channels without passing the two or more pulsed channel current control signals through a regulator, wherein the average current balance element is configured to adjust a channel duty cycle of each of the two or more pulsed channel current control signals relative to the input duty cycle in response to the two or more current sense input signals.

17. A light emitting diode (LED) control method, comprising:

receiving, by an average current balance element, a pulsed control signal input characterized by an input duty cycle and two or more current sense input signals, wherein each of the two or more current sense input

signals is indicative of a current through a corresponding LED channel of a plurality of LED channels;

providing, by the average current balance element, two or more pulsed channel current control signals to two or more corresponding dimming controls correspondingly coupled to the plurality of LED channels, wherein each of the two or more dimming controls is configured to provide an output signal directly coupled to a corresponding one of two or more ON-OFF switches without passing the output signal through a regulator, each of which is coupled in series with a corresponding one of the plurality of LED channels; and

adjusting, by the average current balance element, a channel duty cycle of each channel current control signal relative to the input duty cycle in response to the two or more current sense input signals.

18. The method of claim **17**, further comprising using the two or more current sense input signals to determine a particular channel of the plurality of LED channels having a lowest LED current and provide a feedback signal to a boost or buck converter element configured to regulate a voltage across the plurality of LED channels.

19. The method of claim **18** wherein the particular channel with the lowest LED current has a channel duty cycle equal to the input duty cycle.

20. The method of claim **19**, wherein each of the plurality of LED channels having a higher LED current than the lowest LED current has a channel duty cycle lower than the input duty cycle.

21. The method of claim **20**, wherein a given LED channel other than the particular LED channel having the lowest LED current has a channel duty cycle equal to a product of the input duty cycle and a ratio of the lowest LED channel current to a channel current for the given channel.

22. The method of claim **18**, wherein the boost or buck converter element is configured to sense a channel current through each of the plurality of LED channels and regulate a drive voltage supplied to the plurality of LED channels.

23. The method of claim **22**, wherein the boost or buck converter is configured to receive the two or more current sense input signals, determine two or more switch signals from the two or more current sense input signals, and provide two or more switch signals to two or more switches that are configured to regulate the drive voltage by regulating a current through the two or more switches.

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